Research on ship-hull plate’s curve forming by means of line heating with variable velocity

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Abstract: Line heating (LH) technology is the main process mode in ship-hull plate’s curve forming. Generally, operators implement LH process with constant velocity which is easy and convenient to realise. However, phenomenon of ‘non-uniform deformation’ is easily generated along heating path. The paper studies the root of the phenomenon and puts forth a new kind of LH technology with variable velocity. Internal relationship between temperature field and deformation field under the new technology is studied by numerical simulations. Simulation results show that the new technology can alleviate negative effects of the phenomenon effectively.

Keywords: line heating; non-uniform deformation; variable velocity.


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1 Introduction

Line heating (LH) technology is the main process mode in ship-hull plate’s curve forming which is a kind of highly technical thermo-mechanical forming process in ship production. There have been many fundamental studies on LH technology that focused on plates’ deformation. Martin (1999) and Yu et al. (2001) established the numerical simulation model of LH process and analysed the distribution of temperature field, the stress and deformation field. Shin and Lee (2002) proposed a non-dimensional relationship between input parameters and final deformation during LH process by using the flame heat. Park et al. (2008) developed a software framework for heating line computation, tested it with real ship hull pieces, and verified that the information from the algorithm matches worker’s know-how in practice. Nguyen et al. (2009) established a kind of a model based on artificial neural network to determine positions of induction heating lines and their heating parameters to form a desired shape of plate. Biswas et al. (2009) obtained minimum strain configurations so that least amount of raw material is used and at the same time the work required to produce the desired surface is also minimised. Hui et al. (2013) developed new meshing technique that ensures the accuracy and accelerates computing speed greatly. Ji et al. (2009) developed new method of an automatic line-heating process for the double-curved shell plates. Qi et al. (2013) proposed two coupling parameters to reflect the relation between heating parameters and final residual deformation fairly well. Vega et al. (2013) described the effect of previous heating on inherent deformation by following heating, more specifically, the case of two heating lines applied parallel to each other.

Generally, operators heat the plates by oxyacetylene flame with constant velocity. However, LH process with constant velocity will result in the phenomenon of ‘non-uniform deformation’ along heating path, which affects plate’s processing precision directly. Therefore, it is necessary to explore the root of the phenomenon and develop corresponding solutions, which is conducive to further improvement of plate’s processing precision.
2 Phenomenon of ‘non-uniform deformation’

Heating velocity is an important parameter for the LH process to affect ship-hull plate’s deformation directly, because it influences not only heat energy applied to plates, but also heat diffusion velocity inside plates. Figure 1 shows the distribution law of bending angle along heating path under the condition of different heating velocities and certain acetylene flow (1,100 h/1), where the heating velocities are 2.1 mm/s and 2.3 mm/s. It can be seen from Figure 1 that different velocities will affect plate’s deformation along heating path and result in the phenomenon at different levels.

![Figure 1](image1.png)

3 Root of ‘non-uniform deformation’

In order to reveal the root of ‘non-uniform deformation’ in LH process, the temperature field is analysed. Figure 2 shows the peak temperature’s distribution along the heating path. At the beginning of heating process, the temperature rises rapidly to about 780°C and keeps steady until the end of heating process. The temperature distribution is that the temperature at heating end is higher than that at heating start. The distribution can explain the difference between bending angles at heating end and heating start in Figure 2. Thus, it is obvious that the temperature distribution along heating path is one reason for the phenomenon. Meanwhile the geometric constraint of different points along heating path is not the same in the plates, which is another reason for the phenomenon in the heating course.
4 LH process with variable velocity

Based on the above analysis of the phenomenon of ‘non-uniform deformation’ in LH forming, it provides foundation to alleviate negative effects of the phenomenon. There are two main reasons for the phenomenon: one is temperature field generated by heat source, and the other is geometric constraint of materials. The geometric constraint is difficult to change. Therefore, the most direct idea is to balance the change of geometric constraint along the heating path through the change of the non-uniform temperature field. And the change of the temperature field can be achieved by changing line energy of heat source’s input. Generally, changing line energy can realise the change of the total energy of heat source’s input by changing action time between heat source and materials which is equal to changing the heating process’s velocity.

4.1 Finite element modelling of heating process at variable speed

Deformation field model’s input for LH forming is the calculation results of temperature field model’s output in finite element analysis. Therefore, the deformation field model with variable velocity is consistent with the model with constant velocity. The temperature field model with variable velocity can be established only by modifying the temperature field with constant velocity.

By analysing the finite element modelling method of moving heat source based on ANSYS software platform, heating mode with variable velocity can be achieved approximately as long as changing action time of heat source is applied in each unit. For example, \( t_0 \) is action time in the first finite element unit, and then \( t_0 - t \) is the time in the second unit, where \( t \) is the time interval. By analogy, \( t_0 - (n - 1)t \) is the time in the \( n^{th} \) unit. If \( t > 0 \), heat source’s velocity is of constant acceleration. If \( t < 0 \), the velocity is of constant deceleration. If \( t = 0 \), the velocity is of constant speed.
4.2 Heating modes of simple acceleration and deceleration

The paper analyses the influence of heating modes of simple acceleration and deceleration on the phenomenon in LH forming firstly. As shown in Figure 3, variations of 2–2.5 mm/s and 2.5–2 mm/s are set as heating modes under conditions of acceleration and deceleration, respectively. The temperature fields of both heating modes are studied by using the finite element model of temperature field modelled before.

**Figure 3** Velocity variation of simple acceleration and deceleration

![Velocity variation of simple acceleration and deceleration](image1)

**Figure 4** Temperature distribution along heating path of simple acceleration and deceleration

![Temperature distribution along heating path of simple acceleration and deceleration](image2)

The peak temperature distribution along heating path is analysed because the plate’s deformation in LH forming is mainly centralised around the heating path. Figure 4 shows the peak temperature distribution of numerical simulations of two kinds of heating modes which are of acceleration and deceleration. The temperature trend is more obvious in Figure 4 during the course of acceleration heating, the temperature decreases with heating
direction gradually; during the course of deceleration heating, the temperature increases linearly.

The deformation fields under conditions of acceleration and deceleration can be obtained by inputting calculation results of corresponding temperature field into the finite element model of deformation field. Figure 5 shows the change regularities of bending angle along heating path under both conditions. In order to compare with the phenomenon, the bending angle distribution of heating mode with constant velocity is involved in the Figure 5. It can be seen from Figure 5 that heating modes under conditions of acceleration and deceleration can not alleviate negative effects of the phenomenon but aggravate the negative effects on the contrary compared with the heating mode with constant velocity.

Figure 5 Bending angle variation along heating path of simple acceleration and deceleration

In heating mode of acceleration, the bending angle deformation along heating path keeps decreasing after a small increase of the bending deformation at the beginning of heating process. In the heating mode of deceleration, the bending angle basically keeps the rising trend. At the end of the heating process, the bending deformation angle is decreased slightly.

4.3 Heating modes combined with acceleration and deceleration

It can be discovered that the negative effects of the phenomenon can not be alleviated by simple acceleration or deceleration heating through the above analysis of temperature and deformation fields.

Acceleration heating can decrease the deformation along heating path, while deceleration heating can increase the deformation. Thus, the paper plans to apply a combination of acceleration and deceleration to heat the plate. Concretely, heating velocity would rise firstly and then decline (i.e. 2–2.5–2 mm/s). Figure 6 shows the relationships between the heating velocity and heating path position.
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Figure 6  Velocity variation of combined acceleration and deceleration

![Graph showing velocity variation](image)

Being similar to above analysis process, Figure 7 gives the top temperature distribution along the heating path which is similar to ‘V’ shape. In the acceleration phase (heating path from 0 mm to 500 mm), the temperature decreases. In the deceleration phase (heating path from 500 mm to 1,000 mm), the temperature is rising. Although the heating velocity is the same at both ends of the heating path, the temperature reaches the maximum value because heat energy has been accumulated more in the heating end. Thus the temperature along heating path is a basic form of temperature distribution which is low in the middle and high at each end.

Figure 7  Temperature distribution along heating path of combined acceleration and deceleration

![Graph showing temperature distribution](image)

The experimental and numerical values of bending angle’s change along heating path are shown in Figure 8, whose trends of angle’s change are rising. The average angle of heating process with variable velocity is lower than that with constant velocity, but variation of bending angle along heating path is changed from 0.16 degree to 0.06 degree. Although the decrease is small relatively, it is indicated that LH process with variable velocity can alleviate negative effects of the phenomenon to a certain extent.
Figure 8  Bending angle variation along heating path of combined acceleration and deceleration

5 Conclusions

The paper analyses the root of the phenomenon of ‘non-uniform deformation’ and proposes a new method based on variable velocity. Simulation results verify the rationality of the new heating mode which can alleviate the phenomenon of ‘non-uniform deformation’ effectively.

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